Human walking animation based on foot reaction force in the three-dimensional virtual world

By Ken Tsutsuguchi*, Satoshi Shimada, Yasuhiro Suenaga, Noboru Sonehara and Sakuichi Ohtsuka

This paper introduces a method that can generate continuous human walking motion automatically on an arbitrary path in a three-dimensional (3D) modelled scene. The method is based on a physical approach that solves the boundary value problem. In the motion generation stage, natural-looking walking motion, which includes plane walking, walking upstairs and downstairs and walking on a curved path, is created by applying dynamics and kinematics. The human body is approximated as a simple rigid skeleton model, and dynamic motion is created based on the ground reaction force of the human foot. To adapt to the 3D environment, the 3D walking path is divided into steps which are tagged with the parameters needed for motion generation, and step-by-step motion is connected end-to-end. Additional features include fast calculation and a reduced need for user control. The proposed method can produce interesting human motion and can create realistic computer animation scenes. Copyright © 2000 John Wiley & Sons, Ltd.

Introduction

Walking is one of the most important human motions. Though recent computer graphics (CG) technologies have made it possible to generate high-quality human walking motion and apply it to character animations and motion simulations, it is still very difficult and time-consuming to adapt a moving human figure to a virtual scene. Furthermore, generating human motion requires significant user input to achieve adequate realism.

This paper proposes a method that can automatically create human walking motion along an arbitrary walking path in three-dimensional (3D) virtual environments. This method achieves a realistic, highly controllable walking motion, which includes plane walking, walking upstairs and downstairs and walking on a curved path, and greatly reduces the effort required to make complex scenes.

While various methods of creating walking motion have been reported, the traditional approaches are based on kinematics. Though kinematics methods often fail to produce natural-looking motion or automatically adapt the motion to the scene, they are widely used because they have advantages in terms of calculation time and interactive motion editing. Nowadays, owing to the progress of motion capture systems, the position data of natural-looking motion can be obtained without the annoyance of inputting the data manually. Though various methods have been reported that make it possible to edit the motion data so obtained, it is still difficult to adapt human walking motion to match arbitrary terrains.

Physically based modelling using dynamics is an interesting possibility. In robotics, many works towards building actual walking robots have been reported and some schemes have been applied to computer animation as in Reference 5. Though dynamic methods can generate real and natural-looking motion, the cost in calculation time is huge, because the degrees of freedom of the human body are excessive. Hence many researchers have tried to
reduce the calculation time either by using dynamics only partially or combining it with a somewhat limited model. For example, Bruderlin and Calvert combined kinematics with dynamics to accomplish plane walking motion in their Klaw system. Stewart and Cremer introduced a dynamic approach with their Newton system for straight forward walking. Laszlo et al. applied limit cycle control to the open-loop behaviour of walking and balancing, Ko and Badler treated load- or force-attached walking using inverse dynamics, and McKenna and Zeltzer simulated standing posture and passive steps using a 90-degree-of-freedom human figure model.

A critical need is a walking model that automatically adapts to any terrain, because many 3D virtual scenes have been and will continue to be created. Adaptation to the environment requires additional constraints or control models. One of the adaptation approaches is the self-adaptation approach. For example, McKenna and Zeltzer applied a sensor–actuator model for a six-legged model, and van de Panne et al. introduced a PD (proportional–derivative) controller. These approaches aim to find appropriate foot positions, i.e. boundary values, and calculate the appropriate walking motion automatically. However, it is difficult to make the character follow the user’s desired path.

Other approaches include the footprint approach. The foot position or the path of walking is determined first, then the walking motions are calculated to match the given footprints or walking path. Girard and van Overveld and Ko applied kinematic motion generation, van de Panne and van de Panne applied dynamic translation between foot positions, and Ko and Cremer introduced VRLOCO, which estimated next footprint positions from input body centre position and facing direction and moved the human body to follow them with many types of planar locomotion. Bezault et al. introduced an interactive method for handling the trajectories of human walking, and Tsutsuguchi et al. proposed a path-driven approach, which divided the 3D walking path into a sequence of successive foot positions and applied dynamic calculation.

The algorithm described in this paper proceeds as follows.

1. Approximate the reaction force using a combination of analytical functions.
2. Calculate forward walking motion and rotational motion using approximated reaction force.
3. Calculate arm motion using a simplified pendulum model.

This algorithm yields fast and stable calculation and natural-looking walking motion. Using the proposed approach, users can obtain walking motion that adapts to a 3D modelled scene by merely setting the 3D walking path in virtually real time.

In this paper we treat the human body as an assemblage of rigid parts. Figure 1 shows the body structure of the human skeleton model and the degrees of freedom of each.

Figure 1. Structure of the human model
Figure 2. Typical reaction forces for one step. For the lateral force the positive direction is towards the inside of the foot.

joint used in our system. As shown in Figure 1, we apply the right-handed local co-ordinate system to the human body. In our model the human walks always in the positive x direction and y is the vertical axis. The z axis is orthogonal to the x and y axes.

The term ‘step’ means the motion from one heel strike to the next (by the other heel), and the stance leg is the leg whose foot is on the ground during a step; the swing leg is the other leg.

Analysing Walking Motion

Physically, walking motion is generated by the ground reaction force of the stance foot. For straight forward walking, detailed anlayses have been implemented as part of biomechanics, e.g. the measurement of ground reaction force.21 Figure 2 shows the typical ground reaction force of one foot from heel strike to toe off for straight forward walking. Note that for the lateral component in Figure 2 the positive direction is towards the inside of the foot.

The relation between walking phase, step duration and reaction force is shown in Figure 3. The vertical reaction force of one foot has two peaks: one is at toe off of the other foot; the other is at heel strike of the other foot. The following relationships exist for step duration:

\[ T^\text{stance} = T + T^\text{ds} \] (1)

\[ T^\text{swing} = T - T^\text{ds} \] (2)

where \( T \) is the duration of one step, \( T^\text{ds} \) is for double foot support and \( T^\text{stance} \) and \( T^\text{swing} \) are for stance and swing phase respectively. \( T \) can be obtained from the step length \( w \) and the locomotion velocity \( v \) as

\[ T = w / v \] (3)

or from the step frequency (the number of steps in a certain time unit) \( v \) as

\[ T = 1 / v \] (4)

where we make the approximation \( T^\text{ds} = 0.25 T \).

This is a periodic motion with period \( T \). If we can write the ground reaction force as a function of time, the equation of motion for the position \( r \) of the centre of mass of the human body can be approximately written as

\[ M \ddot{r}(t) = F_L(t) + F_R(t) - Mg \] (5)

where \( M \) is the total mass of the human body, \( g \) is the acceleration due to gravity and \( F_L(t) \) and \( F_R(t) \) are the ground reaction forces of the left foot and right foot respectively.

We measured the ground reaction force of several subjects and used the results to generate synthetic motion for straight forward walking and turning movement, plane walking and upstairs and downstairs walking. Figure 4 shows the averaged reaction force for two 30-year-old men and two 20-year-old women. Two kinds of curved walking were measured: one was left foot support and left turn; the other was left foot support and right turn. The stairs rose 16 cm with a tread width of 30 cm. Though our force plate system could measure only vertical reaction force, we discovered several features as follows.

1. All reaction force curves had a similar shape with two peaks at the same timing.
2. There were no significant differences between straight forward walking and curved walking.

3. There were differences in the heights of the first and second peaks between plane, upstairs and downstairs walking.

Hence we heuristically separated straight forward walking from rotational movement and assumed that they were independent of each other. Though this is somewhat technical, this approximation simplifies the equation of motion for human walking and so reduces the computational cost.

We approximated the reaction forces as

\[
F_x(t) = s_x \sum_{k=1}^{3} a_{xk} \sin \left( \frac{2k\pi}{\text{stance} t} \right)
\]

\[
F_y(t) = s_y \sum_{k=1}^{3} a_{yk} \sin \left( \frac{k\pi}{\text{stance} t} \right)
\]

\[
F_z(t) = \pm s_z \sum_{k=1}^{3} a_{zk} \sin \left( \frac{k\pi}{\text{stance} t} \right)
\]

where \(s_x, s_y \) and \(s_z\) are scale factors and, in (6c), + indicates the left foot and - the right foot.

As the progressional reaction force we chose

\[
a_{xk} = -0.14286/2^{k-1} + \delta_{xk} \quad (k = 1, 2, 3)
\]

where \(\delta_{xk}\) are small values representing the characteristic parameters whose default values are zero, likewise \(\delta_{yk}\) for \(a_{yk}\) and \(\delta_{zk}\) for \(a_{zk}\) respectively. For the vertical reaction force we chose

\[
a_{y1} = 1.3 + \delta_{y1}
\]

These values are obtained by least squares fitting against the measured data. Figure 5 shows these approximated functions. We calculated the angles of the human body using these approximated functions. In the dynamic calculations the straight forward walking motion is generated from the progressional reaction force (6a) and the vertical reaction force (6b). Note that we could not measure progressional and lateral reaction forces, so we took measured data for plane walking from Reference 2 and approximated them as above for plane walking only. The forces represented by (6a), (6c), (7) and (9) were used for all terrain patterns.

**Motion Creation for One Step**

The basis of motion generation is one-step walking motion. This section describes the algorithm that creates the one-step walking motion.

We decompose walking motion into three motions: straight forward walking, rotational movement and arm...
between \( P_i \) the same height as \( P_{i+1} \).

The parameters of these conditions sets are calculated after dynamic motion, we specify three sets of conditions. To calculate shown in Figure 6. The details of these parameters are shown in Figure 6(a). Here \( C(x,y,z) \) represents the position of the centre of mass of the human body.

The dynamic parameters are shown in Figure 6(a). Here \( C(x,y,z) \) represents the position of the centre of mass of the human body.

First we approximately calculate the \((x,y)\) components of the position of \( C \), using the ground reaction force following \( F_x(t) \) and \( F_y(t) \) of (6a) and (6b) and the coefficients (7) and (8). In the calculation the scale factors \( s_x \) and \( s_y \) of (6a) and (6b) are iteratively changed to move \( C \) from the initial position to the final position in time \( T \). Although the functions and coefficients of reaction force for upstairs walking and downstairs walking described in the previous section are derived from measurements using stairs with fixed dimensions, we used these functions and coefficients by changing the scale factor. Since at time \( T^{th} \) the reaction force is the sum of two feet, the reaction force for the stance leg is applied together with the precalculated reaction force for the other leg.

Although a torque function might be more appropriate for calculating the angles, we adopted the reaction force because it can reflect the personal characteristics of the walker directly and the user can control the force intuitively.

To calculate the boundary values for initial and final positions, we assumed that the hip position at the heel strike lay in the middle of the step as shown in Figure 8. From this the boundary values for \( C \) and the ankle

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**Straight Forward Walking Movement**

In the calculation of straight forward walking, first the walking motion in the vertical phase is calculated and then the lateral motion is calculated.

The procedure for calculating the motion in the vertical plane is as follows.

1. Calculate the position of the centre of mass of the body dynamically.
2. Interpolate the angles of the stand leg.
3. Calculate the angles of the swing leg dynamically.
4. Calculate the remaining angles kinematically.

The dynamic parameters are shown in Figure 6(a). Here \( C(x,y,z) \) represents the position of the centre of mass of the human body.

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**Figure 6. Dynamic parameters of human model: (a) forward walking; (b) rotational movement; (c) arm swing**

**Figure 7. Curved step**

swing. We assume that they are independent of each other in terms of their equations of motion; all motions are calculated using dynamics and kinematics.

The procedure to calculate these motions is as follows. The dynamic calculation precedes the kinematic calculation which corrects or exaggerates the motion. The dynamic parameters for one-step walking motion are shown in Figure 6. The details of these parameters are described in the following subsections. To calculate dynamic motion, we specify three sets of conditions.

1. Geometric boundary values—to adapt to the given terrain, we should obtain the initial position (or angle) and final position (or angle) of the human body.
2. Dynamic boundary values—to connect the motion of each step seamlessly, position (angle) or velocity should be preserved at the bounds of each step.
3. Range of motion—to realize natural motion, a range of motions should be available.

The parameters of these conditions sets are calculated after finishing the path setting procedure.

**Figure 7 shows an example of one-step motion.** \( P_i \) is the \( i \)th foot position; \( \omega \) and \( h \) are the distance and height between \( P_i \) and \( P_{i+1} \) respectively. \( P_{i+1} \) is the point that has the same height as \( P_{i+1} \) and is horizontally on the line extended from \( P_i \)–\( P_{i+1} \) which makes \( |P_iP_{i+1}| = |P_{i+1}P_{i+1}| \): \( \alpha_i \) is the angle between \( P_iP_{i+1} \) and \( P_{i+1}P_{i+1} \) in the horizontal plane.

During step \( T \), forward walking movement creates \( P_{i-1}P_{i+1} \) motion, and rotational movement is in the direction \( d_{i-1} (=P_{i-1}P_i) \) to \( d_i (=P_{i+1}P_i) \).

After completing the dynamic calculations, the other angles, i.e. angles other than those displayed in Figure 6, are calculated kinematically according to the precalculated range of each angle.
position are determined. This boundary ankle position is used to determine the heel position at the heel strike, as shown later. At the boundary the velocity and angular velocity are preserved.

The angles to be calculated for the stance leg and swing leg are shown in Figure 9. For the stance leg, if $C$ is determined, we can determine the hip angle $\theta_{ST}^1$, knee angle $\theta_{ST}^2$, ankle angle $\theta_{ST}^3$ and toe angle $\theta_{ST}^4$ according to the interpolation technique of the KLAW system. From Figure 8(b) to 8(c) the stance foot and toe (see Figure 9) rotate linearly around the fixed heel position and $\theta_{ST}^4$ is fixed. The heel position can be calculated from the ankle position in Figure 10(b), i.e. the ankle position at the step boundary (shown in Figure 8). For stairs walking we assumed that the heel and toe touch the ground at the same time and that the heel, ankle and toe positions are fixed until Figure 10(b).

From Figure 10(b) to 10(c) the stance foot (see Figure 9) rotates smoothly around the fixed point $M$, i.e. $\theta_{ST}^4$ increases linearly with the predefined angular velocity. Finally, from Figure 10(c) to 10(d) the foot and toe rotate linearly around the toe position, where the toe position and $\theta_{ST}^4$ are fixed and the ratio of rotation is also predefined.

During all periods, $C$, the ankle positions and $\theta_{ST}^4$ are known, so we can obtain $\theta_{ST}^1$, $\theta_{ST}^2$ and $\theta_{ST}^3$ in Figure 9, are calculated by the following technique.

1. The swing ankle follows an orbit curve, i.e. a combination of two third-order curves, that smoothly connects from the position at the toe off to the point at the heel strike.
2. The hip angle $\theta_{SW}^1$ is calculated dynamically as a single pendulum.
3. The knee angle $\theta_{SW}^2$ is interpolated as shown in Figure 9.
4. The ankle angle and toe angle are interpolated from the toe off to the heel strike.

The other angles, which include the upper body, pelvic rotation and head angles, are calculated using linear or sine interpolation between the initial and final angles.

After completing the calculations in the vertical plane, the lateral motion, i.e. the z component of $C$, is determined using the force $F_z$ in (6c) with (9), and related angles are modified according to the length of the body parts. Figure 11 shows the calculation of the physical states of the centre of mass for straight forward walking (one step).

**Rotational Movement**

Rotational movement is generated by the rotation of the body around a vertical line from the standing ankle. We assumed that this rotational movement was completely independent from straight forward walking as mentioned above.

In this paper we generate rotational movement by applying the method described in Reference 20, except for the rotation force. The method proceeds as follows.
The rotational variables are \( \psi_1(t) \), the angle around the standing ankle, and \( \psi_2(t) \), the angle around the standing hip, as shown in Figure 6; \( \psi_1(t) \) represents the torsion around the axis placed over the standing leg and \( \psi_2(t) \) represents the rotation of the body over the stance hip.

As shown in Figure 12, \( d_i \) and \( d_{i-1} \) are the directions of the step as in Figure 7; \( d \) is the direction of the body at time \( t (0 \leq t \leq T) \) in the \( i\)th step. Between \( d_{i-1} \) and \( d \),

\[
\Psi(t) = \psi_1(t) + \psi_2(t) \tag{10}
\]

We also approximated the ratio \( \psi_1(t):\psi_2(t) \approx 2:3 \) according to the range of each angle and calculated the variable \( \Psi(t) \).

For simplification this method adopts a simple model to handle rotation as shown in Figure 12. In this model the human body is approximated as an elliptical pillar whose total mass is \( M \) and inertia moment is \( I_s = I_{cr} + Mr_r^2 \), where \( I_{cr} \) is the inertia moment whose axis of rotation is vertical and passes through the centre of mass of the body. The axis of rotation \( l_s \) is a vertical line that passes through the standing ankle \( O_r \) and the centre axis of the body is offset by \( r_r \) from \( l_s \).

When the only external force applied to this system is \( F_r(t) \), the equation of motion for rotation can be written as

\[
I_s \ddot{\Psi}(t) = r_r F_r(t) \tag{11}
\]

where \( F_r(t) \) indicates the absolute value of \( F_r(t) \); this method assumes that \( r_r \) is constant during rotation.

On the basis of the above model we used a simple step function based on the progressional reaction force to determine the value of force \( F_r(t) \) in (11) (see Figure 13), because

(a) we assumed that the addition of rotation force begins at the beginning of single-leg support and ends when the progressional reaction force is zero, and

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**Figure 11.** Physical state of centre of mass: (a) acceleration; (b) velocity relative to average; (c) position

**Figure 12.** Model of rotational motion

**Figure 13.** Force for rotation
The value \( f_r \) is determined by iterating equation (11) while changing the value \( f_r \) to rotate \( d \) by angle \( \alpha \) during time \( T \). This value is positive for a left turn and negative for a right turn.

Note that the angle of the articulated body is the sum of the angle from the straight forward walking motion and the angle from the rotational movement.

### Arm Swing

The arms are swung while walking to control the body, and in ordinary walking the average swing angles of the upper arm are about 30° forward and 9° back.

Figure 14 shows the arm swing model in our method.

(a) The whole arm angle \( \phi \) is calculated dynamically and the upper arm angle \( \phi_1 \) leads.
(b) The elbow angle \( \phi_2 \) is calculated kinematically.
(c) Then the arm model is rotated around the backbone through the shoulder angle \( \sigma \) and lifted at the armpit by the angle \( \rho \).

First, the whole arm angle \( \phi \) is calculated, because the motion of a double pendulum is not stable. Let \( l_1 \) and \( l_2 \) be the upper and lower arm lengths respectively, \( m_1 \) and \( m_2 \) be their respective masses and \( m \) be the hand mass. \( S \) (X,Y,Z) is the position of the shoulder and \( G \) (x,y) is the centre of gravity of the system that includes the upper arm, lower arm and any weight held in the hand. As shown in Figure 15(a), we assume that the shoulder \( S \) (X,Y,Z) moves in the vertical plane and approximate the arm as a physical pendulum whose fulcrum is \( S \) and mass \( M_a = m_1 + m_2 + m \).

In this model the equation of motion for \( \phi \) is

\[
I_a = \frac{1}{2} M_a R (\ddot{X} \cos \phi + g \sin \phi) = F_a
\]

where \( I_a \) is the inertia moment of the whole arm whose axis passes through \( S \) and is perpendicular to the xy plane.

\[
I_a = \left( m_1 + m_2 + m \right) l_1^2 + \left( \frac{m_2 + m}{3} \right) l_2^2
\]

and \( R \) is the rotation radius of this system and satisfies

\[
R^2 = \frac{1}{4 M_a^2} \left[ I_1^2 (m_1 + 2m_2 + 2m)^2 + 2I_1 I_2 (m_1 + 2m_2 + 2m) (m_2 + 2m) \cos \beta_e + I_2^2 (m_2 + 2m)^2 \right]
\]

The shoulder position \( S \) is calculated using the shoulder rotation \( \sigma \) and shoulder length. The shoulder velocity \( \dot{S} \)
and shoulder acceleration $\dot{S}$ were derived from rotational movement as follows:

$$\sigma(t) = -\text{factor} \cdot \text{pelvic_rotation}(t) \quad (17\text{a})$$

$$X(t) = \text{half_length_shoulder} \cdot \sin \sigma(t) \quad (17\text{b})$$

The angle $\text{pelvic_rotation}(t)$ is calculated kinematically using sign interpolation when creating the straight forward walking motion.

To simplify this structure, we approximated the torque $F_a$ as a step function according to the progressional reaction force as shown in Figure 16. The assumption is that the direction of arm swing is parallel to the progressional direction:

$$F_a(t) = \begin{cases} f_1^a, & 0 \leq t < T^a_s \\ f_2^a, & T^a_s \leq t < T^a \end{cases} \quad (18)$$

where $T^a$ is the time at which the value of the progressional reaction force is zero. $f_1^a$ is the torque for acceleration, $f_2^a$ is the torque for deceleration and these values are determined by calculating equation (14) iteratively while changing these values to satisfy the boundary conditions

$$\dot{\phi}(0) = \dot{\phi}(T) = 0 \quad (19)$$

and

$$\varphi_f(0) = \varphi_f, \quad \varphi_f(T) = \varphi_f \quad (20\text{a})$$

$$\varphi_f(0) = \varphi_f, \quad \varphi_f(T) = \varphi_f \quad (20\text{b})$$

The equations in (20a) are for the forward swing and the equations in (20b) are for the backward swing. In our method, though equation (19) and the preservation of angle and angular velocity at $t=0$ and $t=T$ are strictly considered, equations (20a) and (20b) are not strictly applied to all steps.

Second, the elbow angle is calculated using the value of $\varphi_f$. As this angle should be $\varphi_f \geq 0$, the angular velocity of the elbow is a sine curve around the angle $\beta_f$ from the line extended from the upper arm.

Finally, the shoulder rotation angle $\sigma$ and armpit angle $\psi$ are added: $\sigma$ is derived from pelvic rotation and $\psi$ is set by the user.

**Motion Creation for Successive Walking**

To create walking motion adapted to a given 3D path, we adopted the path-driven approach described in the first section.

First, a 3D path is created by setting control points, connecting adjacent control points and determining the cross-points between the line and the objects of the 3D world. The intersection of two lines is smoothed. The 3D path is then divided into a sequence of appropriate steps according to the terrain and the default value of stride, which includes plane, up, down and so on, as shown in Figures 20(a) and 20(b) (see next section).

Figure 17 shows an example of the walking path after path division. After being divided into steps, the walking path is approximated as a sequence of line segments. In Figure 17, $P_i$ the $i$th path point, is associated with step parameters that include step length $(\omega_i)$, step height $(h_l)$ and step angle $(\alpha_i)$. If two successive points have the same
horizontal position, only the higher point is considered as at path point $P_i$.

As described in the third section, $w_i$ is the horizontal distance between $P_i$ and $P_{i+1}$, and $a_i$ is the signed angle between $P_{i-1}P_i$ and $P_{i+1}P_i$.

To calculate the one-step motion of the $i$th step, the stance foot is set at $P_i$ and the swing foot is moved from $P_i$ to $P_{i+1}$; this needs geometric parameters, $[M_i, T_i, w_i, h_i, w_i, h_i, a_i]$. Here $M_i$ means the ‘standing leg’, i.e. ‘left’ or ‘right’, and $T_i$ means the $i$th step duration, which can be obtained from $w_i$ and the locomotion velocity $v_i$ according to (3) or from the step frequency $v$ according to (4). We denote this path point as step object $S_i$.

In calculating the one-step motion described in the third section, the parameters $[M_i, T_i, w_i, h_i, w_i, h_i, a_i]$ are used for straight forward walking motion, the parameters $[M_i, T_i, a_i]$ are used for rotational movement and the position of $P_i$ is taken as the local origin. In straight forward walking motion the appropriate vertical reaction force is applied according to the value of $h_i$ and in turning left or right the turn direction is determined by the sign (±) of $a_i$.

The boundary conditions for motion generation or the appropriate kinematic parameters such as range of motion and the average position of certain parts of the body in one-step walking are also calculated according to step object $S_i$ and the walking mode. Mode means continuous motion walking in the same state. The vertical mode includes plane walking and walking upstairs or downstairs, and the horizontal mode includes straight walking and turning to the left or right. These modes can be set using the value of $S_i$.

Figure 18 shows an example of step objects and modes. As mentioned above, by using the step object $S_i$ and kinematic parameters, walking motion of the $i$th step can be generated, and each step is connected continuously by

![Figure 19](image_url)  
**Figure 19.** Examples of generated walking sequence: (a) going downstairs; (b) turning to go upstairs, (c) curved walking

![Figure 20](image_url)  
**Figure 20.** Example of creating a walking sequence: (a) setting walking path; (b) creating step objects; (c)–(e) walking scene
Figure 21. Generated walking sequence: view from left to right, from top to bottom
preserving velocity or angular velocity and position or angle at the step boundary.

Results and Discussion

Figures 19–21 show examples of walking sequence generation. It is obvious that our method created real walking motion that matched the 3D modelled scene effectively. Simply setting the walking path such as in Figure 20(a) allows us to create realistic walking motion.

All the above algorithms were implemented in OpenGL® and SGI OCTANE® (R10000/195 MHz) with \( v = 100 \text{ min}^{-1} \), i.e. 100 steps per minute. In this case we could obtain real time calculation for the case of 30 frames per second. However, there appeared one or two frames delay at the boundary of steps, because the calculation for the next step is executed at the heel strike.

In this paper:

1. We approximated the progressional and lateral forces using data based on plane walking \( ^{21} \) for all walking patterns because we could measure only the vertical reaction force.
2. We approximated the force or torque for rotational movement or arm swing by a step function according to the progressional reaction force because we could not measure them.
3. We used iterative calculations to determine the coefficients of approximated reaction force to adapt to a wide variety of terrains. This was necessary because our approximations for vertical reaction of up or down walking were based on measurements conducted on stairs with fixed dimensions.

The quality of the animation results (see Figures 19 and 21) confirms that our approximations of the reaction force and our model for creation of walking motion that treat three submotions as independent are reasonable for this application.

For the viewpoint of further enhancing animated motion, it is important to be able to create motion that has ‘personality’. We applied the approximation of the reaction force to the averaged values and set the characteristic parameters \( \delta_{ik}(i=x,y,z; k=1,2,3) \) in (7)–(9) as zero, which yields non-characteristic motion. Our next step includes elucidating the relationship between the characteristic walking motion and the characteristic parameters \( \delta_{ik} \).

Our current equipment allows only the vertical reaction force to be measured. We intend to measure and analyse the progressional and lateral reaction forces for various terrain patterns and extract a more sophisticated relationship between them and the force or torque for rotational movement or arm swing.

Furthermore, to enhance the quality of the motion, we will add a balance term that covers the influence of arm swing or rotation on (5).

Even in its present state the proposed approach can create walking motion along 3D walking paths that are set by simply inputting the control points that delineate the walking path. It offers several advantages, including reduced loads placed on the animator.

Conclusion

We described a method for the automatic creation of human motion along arbitrary walking paths based on the reaction force of the foot in the 3D virtual world.

The features of the method are

(a) creation of path-driven walking motion.
(b) generation of realistic walking motion, including straight forward walking movement, rotational movement and arm swing, using dynamics and kinematics, and
(c) applying the ground reaction force to simplify walking movement calculation.

This method offers a very simple way of creating complicated walking motion, including plane walking, upstairs or downstairs walking and curved walking, with just a few parameters. The reaction force approach offers stable and fast calculation and allows a wide variety of walking motion to be created by directly controlling the reaction force function coefficients; it greatly reduces the load placed on the animator.

We are considering the remaining problems and the future work mentioned in the previous section.

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References

Visualization & Computer Animation

WALKING ANIMATION IN THE 3D VIRTUAL WORLD


Authors’ biographies

Ken Tsutsuguchi is a research engineer in the Media Creation Project at NTT Cyber Space Laboratories. He received a Bachelor’s degree in 1989 and a Master’s degree in 1991 from the Kyoto University. Since joining Nippon Telegraph and Telephone Corporation (NTT) Electrical Communications Laboratories (ECL) in 1991, he has been engaged in research on computer graphics and computer animation. His current research interests include computer animation and mixed reality. He is a member of the Information Processing Society of Japan (IPSJ), the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan, IEEE and ACM.

Satoshi Shimada is a senior research engineer in the Media Processing Project at NTT Cyber Space Laboratories. He received BS and MS degrees in electrical engineering from Kanazawa University, Ishikawa in 1984 and 1987 respectively. He joined ECL, NTT in 1987. His research interests include image processing, computer vision and pattern recognition. He is a member of ITE and IEICE.
Yasuhito Suenaga PhD is a professor in the Graduate School of Engineering at Nagoya University. His research interests include image processing, computer vision and computer graphics for better human interface. He received BE, ME and PhD degrees in electrical engineering from Nagoya University in 1968, 1975 and 1974 respectively. In 1973 he joined ECL, NTT and for 24 years conducted various research projects on image processing. From 1985 to 1986 he was a visiting researcher at MIT Media Laboratory, MIT, Massachusetts, U.S.A. Since 1997 he has been supporting Nagoya University as a professor in the Department of Computational Science and Engineering, Graduate School of Engineering. He received the Younger Engineers award from IEICE in 1979. He has been active in various academic societies, including CGI '92 local arrangement chair, IAPR-MVA '92 programme chair, 1992–1994 editor-in-chief of the Group-D Transactions of IEICE, 1998–1999 vice-president of IEICE Information System Society (ISS) and 1997–1998 chair of the IEICE-ISS Technical Group on Pattern Recognition and Media Understanding (PRMU). He is a member of IEICE and IPSJ.

Noboru Sonehara PhD is a project manager in the Media Creation Project at NTT Cyber Space Laboratories. He received BE and ME degrees from Shinshu University, Nagano in 1976 and 1978 respectively. In 1980 he joined ECL, NTT and worked on the development and application of facsimile. From 1988 to 1991 he was with the Auditory and Visual Perception Research Labs, Advanced Telecommunications Research Institute International (ATR) and worked on information processing in neural network. In 1991 he joined NTT Human Interface Labs and pursued various research projects. His current research interests include content engineering. He is a member of IEICE.

Sakuichi Ohtsuka PhD is a group leader in the Media Processing Project at NTT Cyber Space Laboratories. His current research interests include human vision and image processing. He received BE and ME degrees from Kanazawa University, Ishikawa in 1978 and 1980 respectively. In 1980 he joined ECL, NTT and worked on the development of visual communication terminals and in research on image quality evaluation methods. From 1993 to 1996 he was with Human Information Processing Research Labs, ATR and researched on human vision, especially stereopsis. In 1993 he joined NTT Human Interface Labs. He is a member of ARVO, ITE and IEICE.